

Whole Ship Impact Assessment of Mission and Subsystem Choices for Sealift Ships

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ABSTRACT

The design of high-speed ships is examined with a focus on identifying the impact of mission requirements on the selection of ship systems. A unique whole-ship design synthesis model, PASS, that emphasizes the use of physics-based algorithms, is employed to give greater confidence in examining the effect of technology enhancements than is possible with traditional empirically based tools.

INTRODUCTION

The ability to design, construct, and successfully operate ships that achieve high speed in dynamic ocean environments is a continuing challenge to the international marine community. Fast ships can offer important advantages in both commercial and military applications. However, for future development, it will be essential that these fast ships be commercially viable to satisfy either an existing market or, perhaps, a new market that could be generated to meet the perceived need that exists between the transportation of low-cost, low-speed sea freight and high-cost, high-speed airfreight.

Many studies in support of high-speed intra and inter theater military transport of the future envision an array of high technology ships, bristling with the latest and best technologies - fuel cells, integrated electric plants, and full automation, to name but a few. These are exciting visions, and the benefits these new technologies offer are often clearly evident. However, the pace of technology advancements is steadily increasing. Numerous technologies are being developed in all fields of interest to the naval community, ranging from advanced propulsion system concepts and components to advances in electronics and automation. At any one time, several candidate technologies within a single field of interest will be in the 'pipeline' for consideration for application to future ships. How can the 'ship of the future' be designed to take advantage of all of these new technologies? Which of the competing technologies should the acquisition process include?

Historically, the more promising technologies are funded through a variety of sources, leading to prototypes of the technologies being built and tested. The best technologies are then introduced into the fleet. However, in the current environment of limited funding for research and development, sufficient funding is not always available to continue this course of develop, design, test, and introduce. A process, or tool, to evaluate these new technologies in an objective and unbiased manner, so that the relative merits and shortcomings can be quantified and the correct technology decisions made is required. Such a tool would assist in answering questions such as:

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- What does it take to integrate the technology into a ship (i.e. a thorough study of the technology and its impact on the ship)?
- What is the cost to accomplish this and how do alternate technology candidates rank?

Such an assessment needs to be made at the whole-ship or fleet level, and to do so, it must integrate, or synthesize, the new technology with the rest of the ship design. This would then also help answer questions vital to the feasibility of high-speed sea transport such as:

- Is it scientifically feasible to produce large, fast ocean-going ships with today's or tomorrow's technology to affordably carry a military useful load over a military useful distance?
- If so, can such ships be considered commercially viable?

Since the combinations of size and speed examined were to be far outside the norm of current ships, design synthesis models that are based on historical data are not suitable for this application. The incorporation of capabilities to include emerging technologies in synthesis models will result in their use with greater reliability to help shape realistic investment strategies for future research and development. This requirement is a challenge that calls for the use of physics-based algorithms that will allow us to depart from our existing, or prior, technology base and to incorporate new technology trends as and when they occur. This has led to the development of a new generation of design synthesis models. These tools are unique inasmuch as they use, to whatever extent practical, algorithms derived from first-principle physics rather than from empirical data to characterize all major subsystems and their relationship to the overall ship. This ensures that new technologies are realistically modeled without being biased by existing (and maybe out-dated) trends in ship or ship-subsystem design.

PASS, for "Parametric Analysis of Ship Systems" (Lavis & Forstell, 1999; Balasubramanian & Barlin, 2000) is a physics-based design synthesis model that satisfies this emerging requirement. The parametric nature of PASS is ideal for quick exploration of the design space, or, for examining the sensitivity of ship characteristics to changing requirements or subsystem choices. A principal strength of PASS, and hence its application as an efficient tool to evaluate system and subsystem options, is the program's capability to model a realistic mission profile and operating sea conditions while designing a vessel

Currently, PASS has been set up to model a very wide range of ship types including: fast ferries, research vessels, combatants and naval auxiliaries. Advanced ships that can be modeled include SWATH, semi-SWATH, catamarans, trimarans, slender displacement monohulls, planing and semi-planing monohulls, surface effect ships and air cushion vehicles. Verified advance technology capabilities include waterjet and podded propulsion, electric drives, pollution control, fuel cell power plants and advanced composite structures. Intrinsic capability for technology innovation characterized in terms of its mass properties, energy-needs, geometry and cost to develop, build and operate is included in PASS, as illustrated in Figure 1 (from Lavis & Forstell, 1999). Including this information along with the other inputs required to describe the type and operational needs of the ship(s) being examined will allow the user of PASS to determine the whole-ship cost and performance impact of the innovation. Comparing this with the investment cost to develop the innovation will then allow the user to judge whether the investment would be worthwhile.

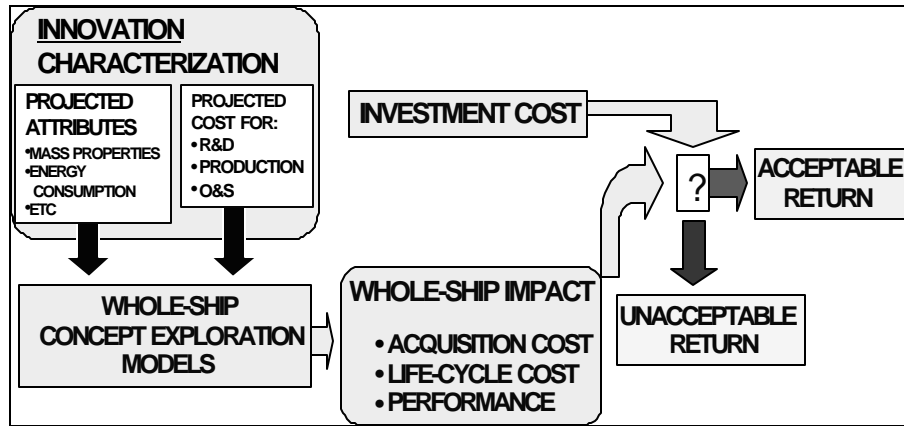


Figure 1. The Approach to Answering: What R&D is Worth Pursuing? Or, What Return Will We Get On Our Investment? (from Lavis & Forstell, 1999)

Other typical uses include those in which the impact of changing operational requirements are easily examined and those in which design to cost trade-offs are conducted for determining the preferred selection of ship type and size, as well as subsystem choices including the choice of hullform geometry, hull structural material, power plant and propulsor type and arrangement. Choices are also made within set limits of stability, seakeeping and state-of-the-art restrictions on feasible geometry. In addition, with PASS, the designer or technologist can optimize vessel and fleet size for minimum acquisition or life-cycle cost.

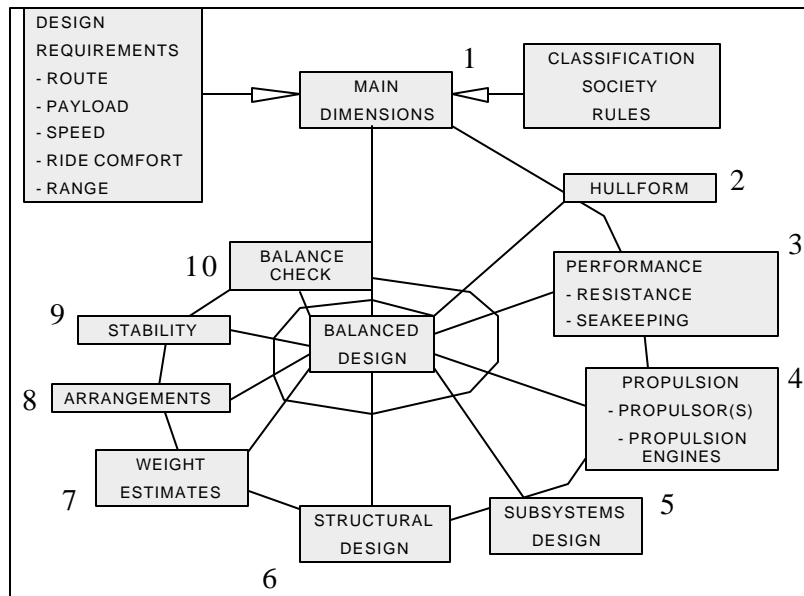


Figure 2. Naval Architectural Design Spiral Simulated in PASS

PASS automates the naval architectural design spiral in order to produce, for a given set of design and operational requirements, a balanced design for which all of the important interactions between subsystem characteristics (weight, volume, energy needs and cost etc.) have been accounted for and are internally consistent with each other. Figure 2 provides a graphical depiction of the standard design spiral. The design process starts with a set of design requirements which includes items such as:

- Maximum Payload Weight
- Required Payload Volume

- Range at Cruise Speed
- Cruise Speed
- Speed/Time Operating Profile

At Step 1, (Main Dimensions), the range of main dimensions of a particular point design are sought based on either user-specified input or default values. The dimensions include:

- Increments of Lengths on the waterline (LWL) to be explored.
- Increments of Beam on the waterline, which is set through user-specified length-to-beam (L/B) ratios to be explored.
- Maximum length of superstructure expressed as a percentage of the LWL.
- Maximum breadth of superstructure expressed as a percentage of overall beam.

At Step 2, the user-specified dimensional information from the initial dimensions of Step 1 is combined with other non-dimensional user-specified hullform characteristics to establish an initial estimate of the hullform. This hullform includes a simplified 3-D representation of the entire ship. In order to do this, it is necessary to make an estimate of the full-load displacement on the first iteration around the design spiral. Subsequent iterations around the design spiral will use the calculated full-load displacement from the previous iteration for hullform development. Some of the primary output from this step includes: (1) the number of decks in the ship's hull, and (2) total volume available in the ship's hull and total area available on each deck.

At Step 3, Performance, the resistance and seakeeping of the hullform, which was established in Step 2, are calculated. This evaluation is accomplished for up to eight different user-specified speed/sea state conditions. At Step 4, Propulsion, the entire propulsion system is designed. This includes the design of the propulsor(s), the power transmission, the propulsion prime mover(s) and associated systems. The propulsion system can be either a mechanical-drive or electric-drive system. The propulsion machinery is sized to match the most demanding speed/sea state case from Step 3. Subsequently, the propulsion system characteristics (power consumed, fuel flow, rpm, etc.) are evaluated at the remaining "off-design" speed/sea state conditions specified by the user. All propulsors are designed using a modified classical axial momentum theory and mechanical power transmissions are designed dependant on gear hardness for example.

At Step 5, the electrical systems, auxiliary system and outfitting are designed. Note that the ship's command and control system (SWBS Group 400) and armament system (SWBS Group 700) are user-specified input and are not calculated or designed by PASS. The electrical system is designed based on a complete electrical loads analysis that follows current naval and commercial design practice.

The ship's structure is designed in Step 6. Here, both local and global loads are calculated and used for sizing the structural scantlings starting with minimum gage and increasing plate thickness and primary structure until local and then global strength and deflection requirements are met based on material properties. These scantlings are used to estimate the weight of the ship's structure based on the material properties (stress allowable, modulus and specific weight). At Step 7, Weight Estimates, the calculated weights of all the ship's systems and subsystems are added together to establish a calculated lightship weight. Subsequently, all ship's loads are calculated and summed. Noteworthy is the manner in which the ship's fuel load is calculated. The program can estimate the fuel load based on two methods. In the first method, the cruise speed and specified range are used in conjunction with the fuel consumption rate that was calculated for the cruise condition in Step 4 to calculate the fuel required to transit the required distance. In the second method, the user-specified speed/time operating profile is used in conjunction with the associated propulsion system characteristics to establish the total fuel load that is required to complete the speed/time profile that was specified for the ship. The fuel loads calculated by these two methods are compared together and the largest value of fuel weight is

added together with the other calculated loads to establish the design value for ship's loads. These loads are then added to the calculated lightweight of the ship and required margins for design and service life are applied to establish a calculated full-load displacement.

The ship arrangements are organized in Step 8. The required deck area and volume necessary to support all of the ship's systems and loads are calculated and compared with the volume that is available in the ship's hull. If the ship's hull does not contain sufficient volume to satisfy the volume demand, the size of the superstructure is increased until the sum of the volume available in the ship's hull and superstructure equals the total volume required to make up the volume deficit, within the limits of the user-specified limits on the superstructure length and breadth in Step 1.

These superstructure length and breadth constraints play a significant role in the PASS design synthesis inasmuch as PASS will initially establish a one-deck superstructure and increase the dimensions of the superstructure, in an effort to balance the volume requirements, until the superstructure length and breadth constant are encountered. If additional superstructure volume is necessary to satisfy the superstructure requirements, PASS will then add superstructure decks until such time as the sum of superstructure volume plus hull volume equals total volume required. This use of superstructure to satisfy volume requirements will often drive the height of the vertical center of gravity, which, in turn, has a significant impact on the stability of the ship.

Step 10 determines if a balanced point design has been reached. Here, the full-load weight that was used to establish the hullform in Step 2 is compared with the full-load weight that was calculated in Step 7. A balance is achieved when successive iterations produce full-load weights that are within 0.5% of each other.

HIGH SPEED SEALIFT – OPTIONS

In recent years, there has been a steady increase in the levels of installed propulsion power for commercial ships. Salient results of the 1997 workshop hosted by Naval Surface Warfare Center, Carderock Division, Maryland (Ritter & Templeman, 1998) on High-Speed Sealift, and the post workshop brief-out, indicate that Surface Effect Ships are the least power options for speeds greater than approximately 45 knots with both near-term and far-term propulsion technology. The results of the workshop indicate that advances in lightweight structural design and improved efficiency of prime movers and propulsors are key to achieving ships with speeds in the 60 to 80-knot range.

In this paper, we investigate the impact of technology options and advances in the areas of hull material and propulsion machinery on an existing sealift ship. First, a PASS model of the ship is developed based on available characteristics of the real ship. The principal contributors to the design choices that dictate the size and weight and machinery options are assessed. Choices in HM&E aspects of the design are then assessed in terms of their impact on the payload weight fraction carried by the ship. The relative impact of these elements, as ship speed is increased is also addressed, so that a pathway to determine the choice of technology innovation that provides the best economic potential for the future of sealift is identified. The results of this determination are framed in reference to other concepts for fast sealift that are currently being considered.

PASS MODELING OF EXISTING SHIP

PASS was used in a point design mode, in which, the available geometric information on the existing ship, such as Waterline Length, Length to Beam Ratio, were used as fixed input. Also the requirements such as cargo weight and volumes, design speed and range, crew size and in this case, the shipboard power requirements were specified. Further, design margins that are consistent with current design practice were assumed as applicable. The program was allowed to determine the subsystem weights and power requirements based on these minimum inputs. Figure 3 is a three-dimensional design visualization of the ship as designed in PASS.

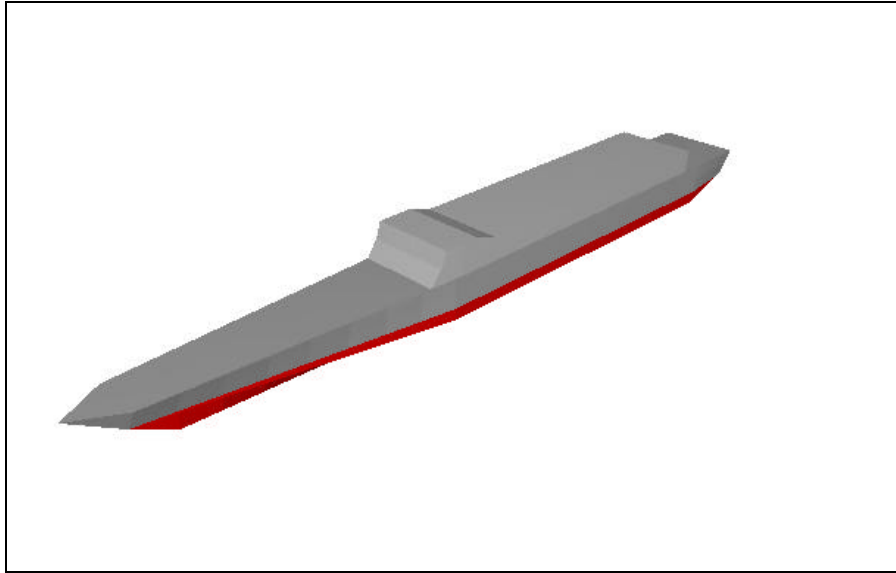


Figure 3. Design Visualization of Existing 24-Knot Ship

A comparison of the specified input variables along with the estimated data to the data available from the existing ship description is shown in Table 1. As seen in Table 1, the agreement in the principal dimensions and powering estimates are good and this is consistent with agreement achieved in using the program to model various other ships. The good agreements in powering and propulsor diameter are indicative of the hullform design being accurate. Therefore, the differences in the full-load displacement are likely a result of differences in the design of outfit and auxiliary systems, which on ships with such capabilities, can be expected to be quite complex.

Table 1. Comparison of Principal Particulars
(* Represents specified input)

Characteristic	EXISTING SHIP	PASS	% Diff
Length Overall (ft)	950.0	957.35	< 1.0
Waterline Length (ft)*	905.0	905.0	
Molded Beam (ft)*	105.75	105.85	
Design Dra ft (ft)	34.0	34.61	< 2.0
Displacement (LT)	62700	60094	< 4.5
Design Speed (@ 90%MCR)*	24.0	24.0	
Range @ Design Speed (NM)*	11990	11990	
Cargo Weight (LT)*	13000	13000	
Cargo Area (sq. ft)*	393700	393700	
Crew*	32	32	
Powering (Gas Turbines) (HP)	GE LM2500	32539	< 2.0
Propellers (ft) (controllable pitch)	24.0	24.43	< 2.0

The weight breakdown for the PASS designed 24-knot ship is presented in SWBS format in Table 2. Included in Table 2 are ratios of the payload weight fraction for the baseline ship based on both the lightship weight and the full-load displacement. The contribution of steel weight to the lightship weight is remarkable and is of the order of 72%. Similarly, the weight of fuel is of the order of 37% of the deadweight of the ship. Reductions in either or both of these contributors will be significant for improving the transport efficiency of the 24-knot ship.

Table 2. Weight Breakdown for 24-Knot Ship

	Weight (LT)
SWBS 100 (Hull Structure)	27221
SWBS 200 (Propulsion Plant)	589
SWBS 300 (Electric Plant)	955
SWBS 400 (Command & Surveillance)	45.0
SWBS 500 (Auxiliaries)	6848
SWBS 600 (Outfit & Furnishing)	1134
SWBS 700 (Armament)	2.0
Lightship	36975
Loads	20649
Full Load Weight	60094
Payload/Lightship Weight Fraction	0.3515
Payload/Full Load Weight Fraction	0.2163

Having identified features of the existing ship that have a large influence the efficiency of the ship, the use of high strength steel as well as potential improvements in the specific fuel consumption of the gas turbine engines that power the ship are considered. In addition to technology advances and hull material, sealift ships with increased speed was considered. Sealift ships with design speeds of 30 and 35 knots were designed using PASS. The hullform of the existing ship was used in these design studies, although, in practice, one would not expect this to be a wise choice for a hull designed for 24 knots. Thus, what was created was just a simple example of the capability of the tool, as the scope of the effort did not permit an in-depth investigation of hull-form parameters, as would normally be the case.

Controllable pitch propellers were used to propel the 30-knot ships, while the 35-knot designs were propelled by waterjets. Further, to achieve the requisite thrust, the number of propulsors and prime movers were increased to four. During the design synthesis modeling effort, it was determined that the 35-knot ships are not capable of carrying the cargo payload of 13000 LT. The increase in speed results in the need for prime movers with powers in excess of currently available prime movers. Therefore, the payload was reduced to half the amount carried by the T-AKR. Table 3 presents principal characteristics of the 24, 30 and 35-knot ships. As seen in Table 3., the installed power increases tremendously with increasing speed and the previously mentioned reduction in payload capacity. Optimizing the hullform for each design speed will alleviate some of the increases in propulsion power. However, given the limited scope of this paper, no hullform optimization or parametric studies to ascertain the most optimum hullform were conducted.

Table 3. Comparison of Principal Characteristics of Sealift Ship Designs

Characteristic	24 knot	30 knot	35 knot
Length Overall (ft)	950.0	957.35	957.35
Waterline Length (ft)*	905.0	905.0	905.0
Molded Beam (ft)*	105.85	105.85	105.85
Design Draft (ft)	34.61	39.95	37.35
Displacement (LT)	60094	69475	65447
Design Speed (@ 90%MCR)*	24.0	30.0	35.0
Range @ Design Speed (NM)*	11990	11990	11990
Cargo Weight (LT)*	13000	13000	6500
Number of Prime Movers	2	4	4
Powering (Gas Turbines) (HP)	32539	41522	65637
Propulsors	VPP	VPP	WJ

COST-BENEFIT OF TECHNOLOGY CHOICES

The whole-ship impact of employing high-strength steel as structural material for the sealift ships was investigated in conjunction with the potential advantages of improving the specific fuel consumption characteristics of the gas turbine prime movers. The high strength (HS) steel used in these investigations, for example, was assumed to have a working strength that is 50% higher than that of the low carbon (LC) steel used for the 24-knot existing ship. Similarly, the potential for gas turbines with substantially lower fuel consumption characteristics was modeled primarily as a percentage reduction in the specific fuel consumption (SFC). Reductions of 10% and 25% of the SFC were considered and represent notionally achievable values in the near term (defined as in the next 5 to 10 years) and in the far term (10–20 years) respectively.

The payload weight fraction (defined as the ratio of payload weight to full-load displacement) as a function of the choice of hull material and design speed is plotted as a function of the % reduction in specific fuel consumption in Figure 4. The baseline 24-knot sealift ship is represented as a reference point and helps identify the improvements to the current state of the art in technology. As would be expected, a significant drop-off in the payload weight fraction is visible for the 35-knot ships and this is primarily due to the increased fuel consumption and therefore reduced payload that these ships carry. Even so, the data in Figure 4 indicates that significant reduction in SFC will be required for the 30 and 35-knot ships to compete with the existing 24-knot ship in terms of its payload weight fraction.

The data in Figure 4 also indicates that the 24-knot ship, designed with the assumed higher strength material for the hull, will possess a nominally higher payload weight fraction (about 13%), primarily driven by the reduction in steel weight for the ship. A similar assessment for the 30-knot ship indicates that the gains in payload weight fraction are not as extensive (about 2%) as for the 24-knot ship. This reduction is a manifestation of the increased propulsion power installed on the 30-knot ship. A preliminary assessment of the results would indicate that the use of lighter prime movers, or in a technology perspective, prime movers with higher power to weight ratio would be beneficial. As a corollary, propulsors with high hydrodynamic performance characteristics would, of course, also be beneficial.

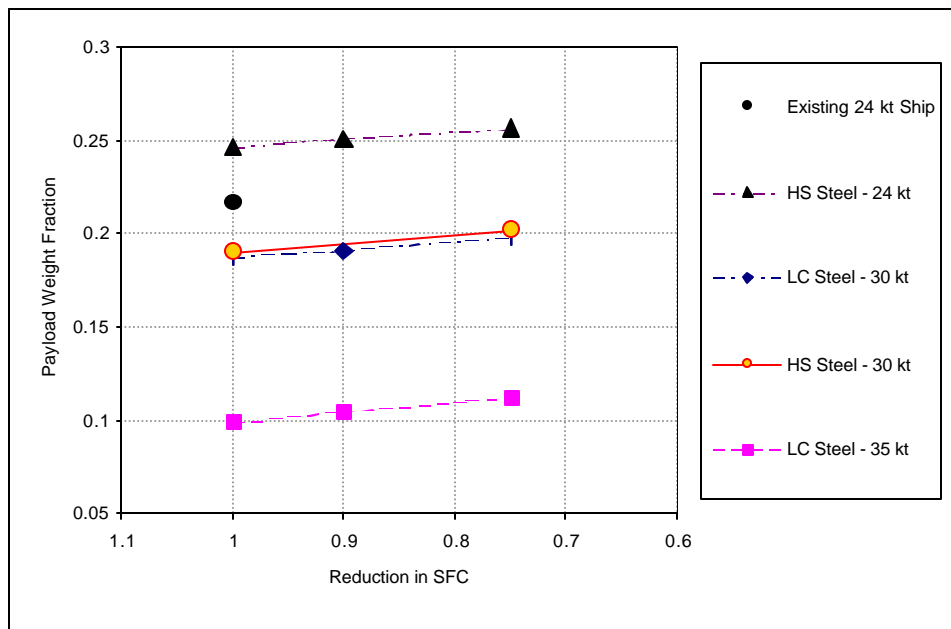


Figure 4. Variation of the payload weight fraction as a function of mission needs and technology enhancements.

Overall, the choice of technology to pursue, based on this limited analysis seems to indicate that reductions in steel weight are more useful to the design of a more efficient sealift ship than is the potential reduction in SFC. This result is not surprising and is what one would intuitively expect. However, the use of PASS has helped quantify the amount of the gain in efficiency and can be very useful as a decision making tool for program managers in developing goals and requirements for new technology.

Having developed a technical rationale for the development of technology roadmaps, an economic assessment of the competing technologies vis-à-vis the mission effectiveness of the various competing platforms is essential to assess the cost-benefit of innovation. A novel method to assess this trade-off is presented in Figure 5. The χ scale in Figure 5 represents “Relative Transport Efficiency” and is defined as the ratio between the payload transport factor of the competing platforms and the baseline 24-knot ship. The transport factor (Kennel et al., 1998) compares competing designs to relate the utility of each design when performing its transport task and is given by:

$$TF = (KW)/(SHP_{\Pi}/V_K), \quad (1)$$

where K is non-dimensionalizing constant, W is the payload weight, SHP_{Π} is the total installed power and V_K is the average ship speed for a voyage (i.e., sustained or service speed). On the y-scale of Figure 5 is the cost of operating the various competing ships relative to the baseline ship over its lifetime. These operation and support costs are determined in PASS and when used in a relative sense is a very useful index to compare various options.

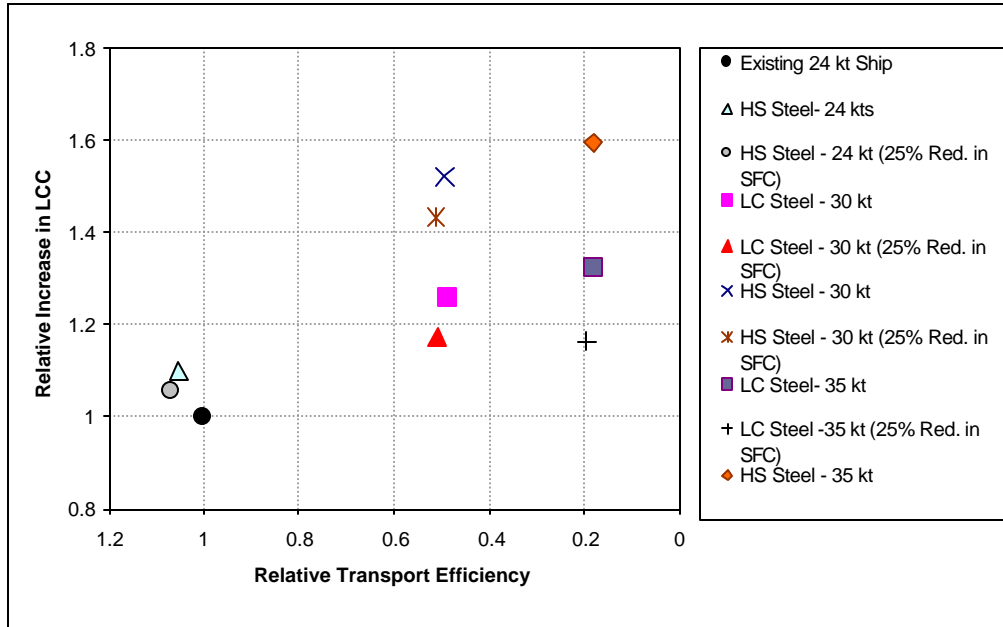


Figure 5. Quantitative evaluation of the cost-benefit of competing technologies

The data in Figure 5 indicates that, within the constraints of this investigation, that reducing the steel weight of the T-AKR can result in a ship with increased transport efficiency at very little increase in operating costs. However, increases in the design speed of these vessels will impose very significant increases in operating and support costs as well as decreases in transport efficiency. Further, it is observed that substantial reductions in SFC result only in almost imperceptible improvements in transport efficiency. While these conclusions are often intuitively obvious, the degree of increase has been quantified here.

CONCLUSIONS

A physics-based design synthesis model, PASS has been employed successfully to quantitatively evaluate the cost-benefit and whole ship impact of mission requirements and technology enhancements for long-range cargo transport using traditional monohull sealift ships. The use of high strength steel as hull material appears to hold promise, while very significant improvements in prime mover efficiencies appear to yield very modest gains. Overall, the power of design synthesis modeling in arriving at rapid and objective solutions to developing technology roadmaps is highlighted.

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